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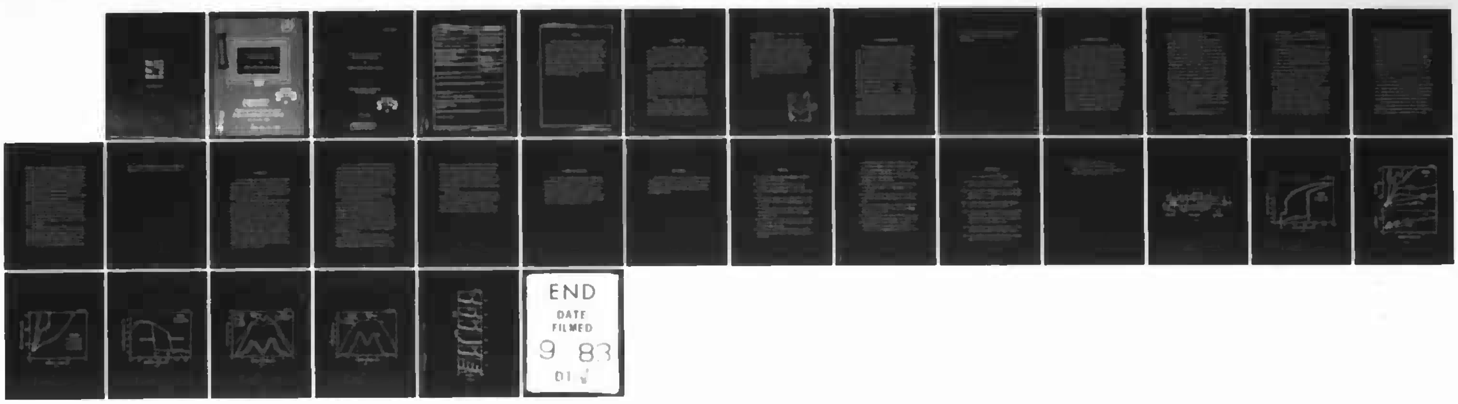

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Observations of Nonlinear Behavior in a Low-Pressure Discharge Column

by

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ABSTRACT

Sudden and abrupt jumps in the plasma density and discharge current of low-pressure magnetized argon and helium plasmas are observed. These jumps are found to depend on the discharge bias voltage, the neutral gas pressure, and the magnetic field strength and occur with a substantial hysteresis in those parameters. These jumps are accompanied by the onset of intense and coherent low-frequency plasma oscillations. In addition, under certain conditions, the radial density profile of the plasma is found to be significantly different following a jump. Some possibly related plasma instabilities are discussed.

I. INTRODUCTION

Recently, there has been a great deal of interest in nonlinear plasma phenomena, particularly in connection with controlled fusion and in laser physics. The necessity for considering nonlinear plasma effects is evident, since nonlinear phenomena are frequently observed in plasmas. Examples of such effects are jump phenomenon, hysteresis, mode competition, and explosive behavior [1].

Sturrock [2] draws a distinction between explosive and nonexplosive instabilities and proposes that a physical system, which exhibits a sudden change in state, had an explosive instability triggered. Similarly, Kadomtsev [3] draws the distinction between what he calls soft and hard excitations, i.e., whether or not the transition to a turbulent state is smooth or abrupt. He points out that the nonlinearity which leads to a hard excitation could lead to hysteresis.

Plasma discharges often exhibit nonlinear and turbulent behavior [3]. An example of an explosive instability is the disruptive instability in tokamaks. Hutchinson [4] directly measured the toroidal current density in the LT-3 tokamak and found that the current can abruptly stop. An example of hysteresis in the electric field versus magnetic field strength in a positive column was found by Robertson and Currie [5].

Here, we report the observations of sudden jumps with hysteresis in low-pressure ($\sim 10^{-4}$ Torr) argon and helium discharges. Our preliminary observations have been previously reported [6]. These jumps occur in the discharge current together with the plasma density when either the magnetic field strength, discharge bias voltage, or neutral gas pressure are varied. Associated with these jumps are the onset of large amplitude plasma oscillations and a modification of the plasma density profile. The plasma parameters were such that $\Omega_e \sim \omega_{pe}$ and $\nu_{\alpha n} < \Omega_{e,i}$ where $\nu_{\alpha n}$ is the neutral species collision frequency and $\Omega_{e,i}$ is the electron, ion gyrofrequency.

II. EXPERIMENTAL APPARATUS

The experimental apparatus used in this experiment is shown in Fig. 1. It consists of three sections with the main chamber, which was made from aluminum, placed in a uniform longitudinal magnetic field variable up to about 7 kG with less than 1 percent ripple. A stainless steel source chamber placed at one end just outside the solenoid contains a 7.5 cm in diameter hot conical spiral filament made of 2.4 mm tantalum wire 165 cm in length from which ionizing primary electrons are accelerated to a grounded stainless steel grid (16 × 16 lines/cm) placed near the solenoid. The field strength at the cathode is about half that in the main chamber. The cathode requires a current of 94 A at about 30 V to produce a discharge of up to 2 A for argon pressures in the 10^{-4} to 10^{-3} Torr range. At the opposite end, a large aluminum chamber contains a movable end plate upon which the plasma is terminated. The system could be pumped down to a base pressure of 1-2 × 10^{-6} Torr.

The diagnostics were carried out in the main chamber using three 1.6 mm tantalum disk Langmuir probes. One scanned horizontally, another scanned vertically, while the third was movable in the axial direction and could also be rotated radially through the center of the plasma column. Typical parameters are: T_e = 1-5 eV,

$n_e = 10^9$ to 10^{11} cm^{-3} with the plasma potential several volts positive and n_i is believed to be $\sim 0.1\ T_e$, as measured in similar plasma devices.

III. EXPERIMENTAL OBSERVATIONS

The most noticeable observations found in this experiment were the onset of sudden transitions in discharge current and plasma density occurring for small changes in either neutral gas pressure, magnetic field strength, or cathode bias voltage. We found that for fixed pressures and field strengths that as the cathode bias voltage was slowly increased, the plasma density changed only slowly until some critical voltage, V_1, where the plasma density, n_p, measured in the center section of the plasma column jumped by a factor of as much as 20. In addition, just before this jump the plasma potential increased slightly (< 2 V) before returning back after the jump. We refer to this as a transition from a lower to an upper state. When, however, the bias voltage is decreased to V_2, the plasma returns to the lower state. A plot of this hysteresis effect appears in Fig. 2. In this particular case, we even observed an intermediate state. In rare instances, we observed several intermediate states (usually in the downward-going transitions), but we will limit our discussion to the main transitions. We have also observed that immediately after the upward transition, n_p, as well as the discharge current, I_d, continued to increase slowly for several minutes. This is possibly due to an increase in the temperature of the cathode due to heating by ion bombardment.

Plots of these critical voltages versus magnetic field strengths for various gauge pressures are shown in Fig. 3. For up-going transitions [Fig. 3(a)], it shows that as the pressure is increased, V_1 decreases and becomes less dependent on the field strength. For down-going transitions [Fig. 3(b)], V_2 varies little with increasing pressure. Between 1 and 2×10^{-4} Torr, the transitions are the most noticeable and correspond to the greatest change in plasma density. Outside this range, the transitions are difficult to find. Below 1×10^{-4} Torr, the plasma is typically in the lower state unless V_1 is very large or the field strength is small. As the pressure is increased above 2×10^{-4} Torr, the transitions becomes less abrupt and the plasma appears to oscillate randomly between apparently closely spaced states, which differ in density by less than 25 percent. If the pressure is increased further, the critical voltages mark the onset of low-frequency noise. It should be noted that at low pressures, the abrupt transitions also become weak if the cathode temperature is lowered slightly. Consequently, it is possible that at higher pressures, these weak transitions would become more abrupt and the states more distinct if the cathode temperature were raised further.

Similar effects were also observed in helium. Plots of V_1 versus magnetic field strength and pressure appear in Fig. 4.

Unlike the argon data, V_1 versus field strength was not found to saturate with increasing helium pressure, but were similar to argon at lower pressures. We also note that the curves exhibited a minimum near 180 G.

In Fig. 5, we show the same hysteresis effect for I_d but for a fixed argon pressure and bias voltage while varing the B field. As B is increased from low values, the plasma remains in the upper state up to a critical field, B_2, where it abruptly drops to the lower state. A further increase in the field results in little or no change in I_d, although the plasma becomes increasingly noisier. This is similar to the anomalous diffusion effects observed by Hoh and Lehnert [7] at much higher pressure and explained by Kadomstev and Nedospasov [8]. Significantly, in our experiment, there is often a hysteresis effect covering 1 kG; although, hysteresis effects covering as much as 3 kG have been observed. When B is decreased to B_1, the plasma returns to the upper state.

Time-averaged radial density profiles were measured by biasing a probe just above the plasma potential to collect the electron saturation current and scanning the probe radially at the central section of the chamber. A series of scans appears in Fig. 6 for fixed pressure and cathode bias voltage. Starting at 370 G, the plasma is in the upper state. The profile shows that the column is fairly broad and flat. As the field is increased above $B_1 = 590$ G to 810 G, the column narrows and becomes more peaked as one would expect with classical diffusion. When the field is increased beyond B_2 = 1100 G to 1650 G, the profile shows a marked change in the spatial distribution and plasma density. Apparently, a profile, similar to a first-order Bessel function, is formed with a hole in the center that is down by 80 percent from the peak density at r = 2 cm. We also found that this hole extends the entire axial length of the chamber from near the filament to the end plate. The hole is even noticeable in the visable light emission from the column. Increasing to higher fields causes no further significant changes. Subsequently the field was reduced back below B_2 to 810 G but the plasma retained this profile: the two scans for B = 810 G were taken with the same external conditions and differed only by the path taken in B.

Similarly, in Fig. 7, we show the same effect occurring in helium. Curve 1 was taken at 150 G with the plasma in the upper state while curve 2 was taken at 2930 G with the plasma in the lower state. Again a significant change in the spatial characteristics is seen. Although we have shown electron saturation current profiles, corrections due to spatial characteristics in electron temperature and plasma potential do not qualitatively change the results.

The transition between the upper to the lower states are accompanied by the onset of intense and coherent oscillations in plasma density. The measurements were made by monitoring the current fluctuations drawn to a probe biased above the plasma potential. The frequency spectrum of these oscillations is shown in Figs. 8(a)-8(e) for several magnetic field strengths. Starting with the plasma in the lower state [Fig. 8(a)] with B = 3.7 kG, a narrow peak around 30 kHz is observed. As the magnetic field is decreased from 2.2 kG [Fig. 8(b)] to 1.8 kG [Fig. 8(c)], the peak shifts to a slightly higher frequency. When the magnetic field is reduced below 0.9 kG [Fig. 8(d)], the plasma jumps to the upper state and the spectral peak disappears. When the magnetic field strength is increased above 1.0 kG [Fig. 8(e)], the plasma returns to the lower state and the spectral peak reappears at 36 kHz.

Under slightly different plasma conditions ($p = 2.5 \times 10^{-4}$), the spectrum shown in Fig. 8(f) is observed. Typically such a harmonic spectrum is observed for proper tuning of the parameters and for B in the range $B_1 < B < B_2$, i.e., within the hysteresis loop. When B is increased, the spectrum tends to shift to higher frequencies and broadens out. Eventually, all peaks disappear and a broad spectrum is observed.

The propagation characteristics of these oscillations were determined with two movable Langmuir probes located in the central section of the plasma. Typically we observed m = 1 and m = 2 modes propagating azimuthally depending on the adjustment of the parameters p, V_b, and B. The phase velocity of these modes (for r = 2-3 cm) is $3\text{-}4 \times 10^5$ cm/sec, slightly higher than the ion-acoustic speed. Preliminary measurements of the parallel wavelength indicates that it was on the order of twice the machine length.

IV. DISCUSSION

The results suggest that a nonlinear instability is triggered for certain critical parameters. This instability may be present throughout the plasma column where it may affect plasma losses or there may be local effects in the source chamber which affect plasma production. We will discuss a number of possible instabilities which could be related to our observations.

An instability that produces anomalous radial plasma losses is the well-known helical or current convective instability in a high-pressure positive column (see a review by Nedospasov [9]). This instability, which was first observed by Hoh and Lehnert [7] and explained theoretically by Kadomtsev and Nedospasov [8], gives rise to a helical distortion of the plasma column above a critical magnetic field strength. Ventrice and Massey [10] provided clear experimental evidence that in the presence of this instability, the radial plasma profile peaks off axis. In addition, Robertson and Currie [5] observed that this instability has a sudden onset with hysteresis. A quasilinear calculation by Simon and Shiau [11] indicates that explosive behavior with hysteresis is possible at low pressures where the stabilizing influence of ion-neutral collisions are less important, i.e., $\Omega_i/\nu_{in} >> 1$.

Alternately, drift instabilities when density gradients are present may increase losses. Observations by Ellis et al. [12], of the collisional drift instability at somewhat higher pressures than ours, indicated that a weak electron current driven through the column from a positively biased grid induces the onset of a single, large amplitude ($\delta n/n > 10\%$) coherent mode, usually $m = 1, 2,$ or 3. The onset was controlled by the grid voltage and could be extinguished by decreasing B, although a different azimuthal mode would set in. A flattening of the radial density profile when the instability was present indicated enhanced radial losses.

A unified treatment of linear theories for low-frequency instabilities in a weakly ionized magnetoplasma is given by Self [13]. He discusses instabilities arising from parallel, Hall, and diamagnetic drifts including those already mentioned. In general, at low pressures, where ion inertia cannot be neglected, all three drifts may be present that can excite various types of waves, each of which has a wide spectrum of eigenmodes. The nonlinear saturation of any single instability may alter the steady-state conditions which effect the onset of other modes making detailed comparisons with experiment difficult.

There are other possible effects, in addition to the instabilities discussed previously, which could be present in our experiment. These effects are related to the plasma production mechanism in which energetic ionizing electrons ($v_{ionz} > v_{th}$) are produced in the source chamber. These ionizing electrons drifting through the background plasma in the source chamber could excite various high-frequency instabilities giving rise to an enhanced resistivity in the region between the cathode and anode. This, in addition to the possible effects of the inhomogeneous magnetic field in the source chamber, could affect the production and flow of ionizing electrons which in turn would affect the plasma production throughout the device.

Dobrowolny and Santini [14] have considered the effects of anomalous resistivity in plasmas confined by strong magnetic fields ($\Omega_e > \omega_{pe}$), as a possible explanation for the onset of the disruptive instability in tokamaks, as seen by Hutchinson [4], for example. Such effects may be responsible for some of the behavior seen in our experiment where the condition $\Omega_e \sim \omega_{pe}$ is satisfied.

V. SUMMARY AND CONCLUSIONS

We have reported experimental observations of sudden jumps and hysteresis behavior in a low-pressure discharge plasma. These effects are possibly associated with the explosive onset of an instability in the plasma which may be related to the presence of various destabilizing drifts or to instabilities connected with plasma production. These phenomena give rise to a substantial modification of the plasma density profile and the existence of plasma states whose accessibility depends on the path taken.

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FIGURE CAPTIONS

Fig. 1. Schematic diagram of plasma discharge device.

Fig. 2. Discharge current I_d vs bias voltage V_b at fixed magnetic field strength showing sudden jumps and hysteresis.

Fig. 3. Critical voltages for up-going transitions, (a), and down-going transitions, (b), vs magnetic field strength for argon plasmas at various pressures.

Fig. 4. Critical voltages for up-going transitions vs magnetic field for helium plasmas at various pressures.

Fig. 5. Discharge current vs magnetic field strength showing sudden jumps and hysteresis. Note that in this case the magnetic field strength was changed slightly as the x-y recorder was responding to the rapidly changing current.

Fig. 6. Radial profiles of electron saturation current ($\propto$ electron density) for various magnetic field strengths in argon.

Fig. 7. Radial profiles of electron saturation current ($\propto$ electron density) for B = 150 G and B = 2930 G in helium.

Fig. 8. Power spectra of electron density fluctuations.

(a) $B = 3.7$ kG, (b) $B = 2.2$ kG, (c) $B = 1.8$ kG,

(d) $B = 0.9$ kG, (e) $B = 1.0$ kG, and (f) harmonic spectrum observed at higher pressures with $B_1 < B < B_2$.

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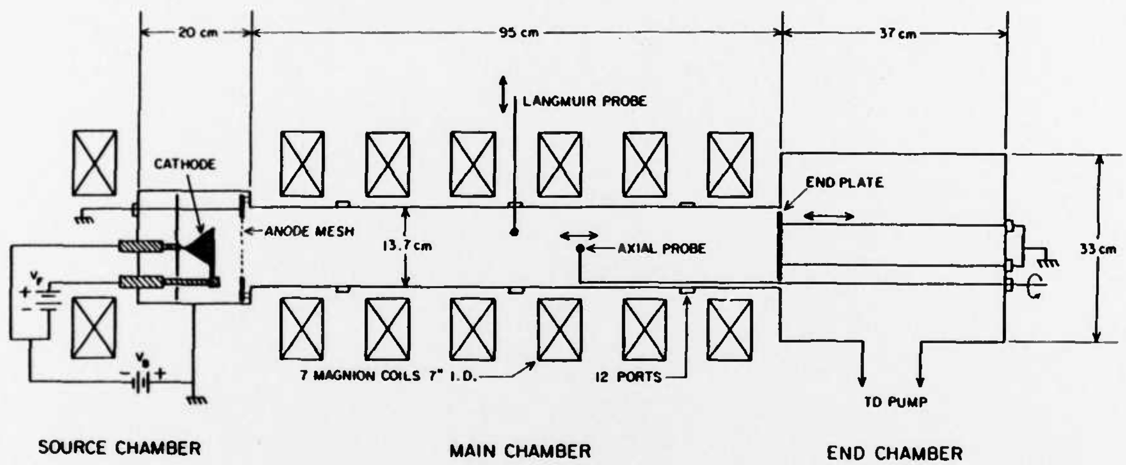


Fig. 1

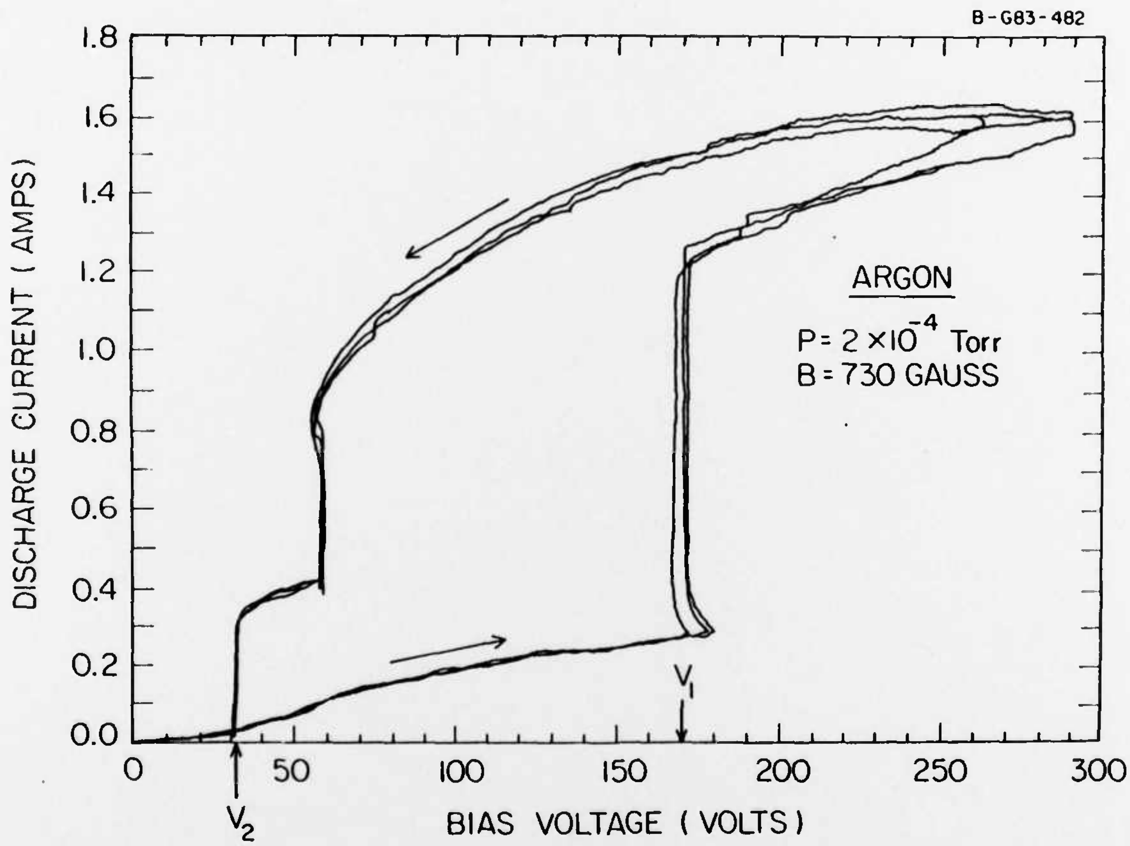
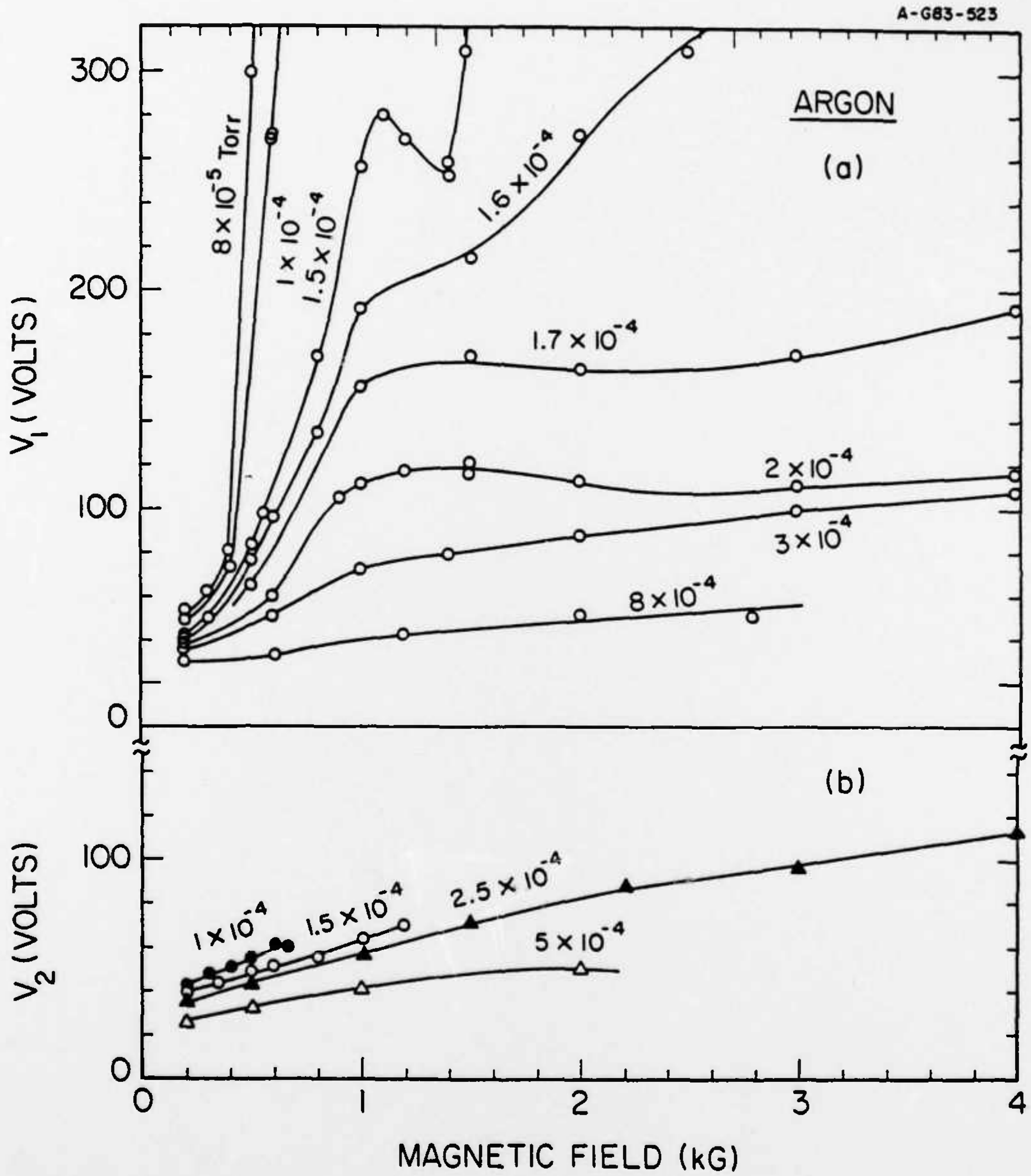

B-G83-482
DISCHARGE CURRENT (AMPS)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
300
BIAS VOLTAGE (VOLTS)
V_1
V_2
ARGON
P= 2 ×10^{-4} Torr
B = 730 GAUSS

Fig. 2



A-G83-523
ARGON
(a)
(b)
300
200
100
0
8×10^{-5} Torr
1×10^{-4}
1.5×10^{-4}
1.6×10^{-4}
1.7×10^{-4}
2×10^{-4}
3×10^{-4}
8×10^{-4}
V_1 (VOLTS)
V_2 (VOLTS)
1×10^{-4}
1.5×10^{-4}
2.5×10^{-4}
5×10^{-4}
0
1
2
3
4
MAGNETIC FIELD (kG)

Fig. 3

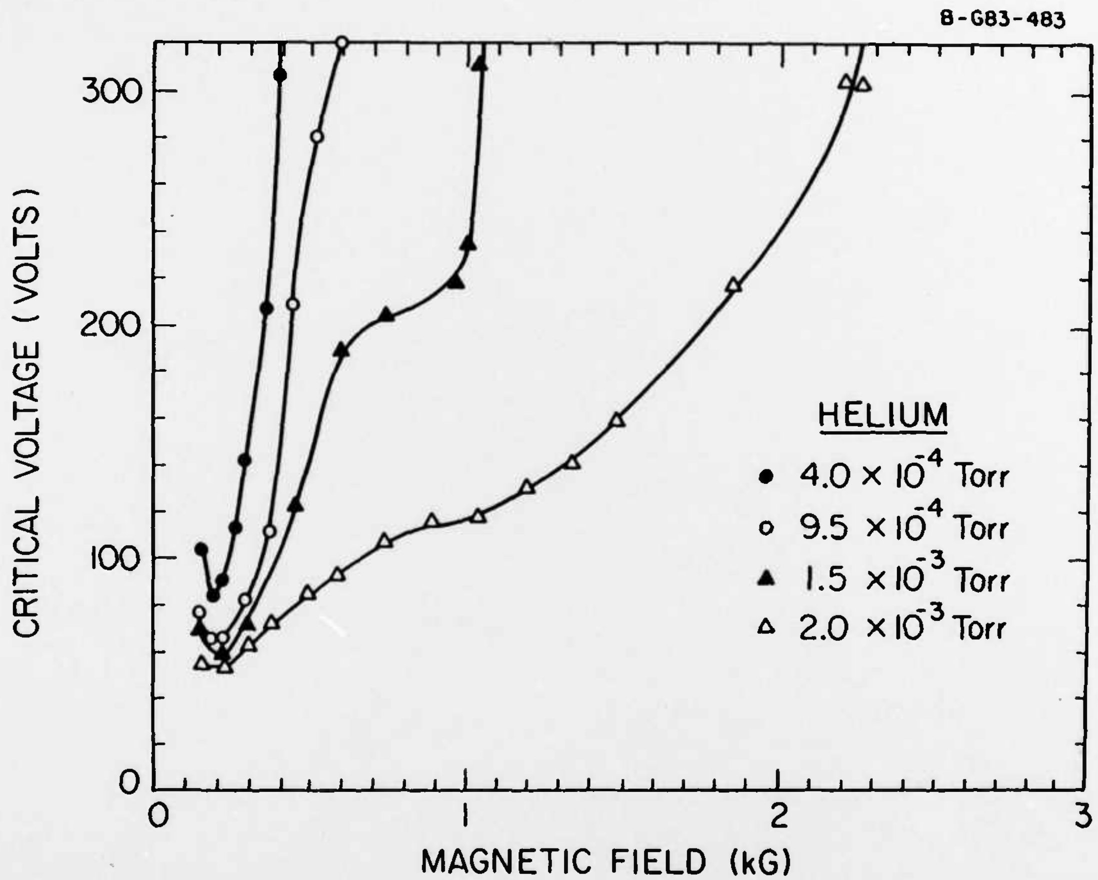

8-G83-483
CRITICAL VOLTAGE (VOLTS)
300
200
100
0
0
1
2
3
MAGNETIC FIELD (kG)
HELIUM
4.0 × 10^-4 Torr
9.5 × 10^-4 Torr
1.5 × 10^-3 Torr
2.0 × 10^-3 Torr

Fig. 4

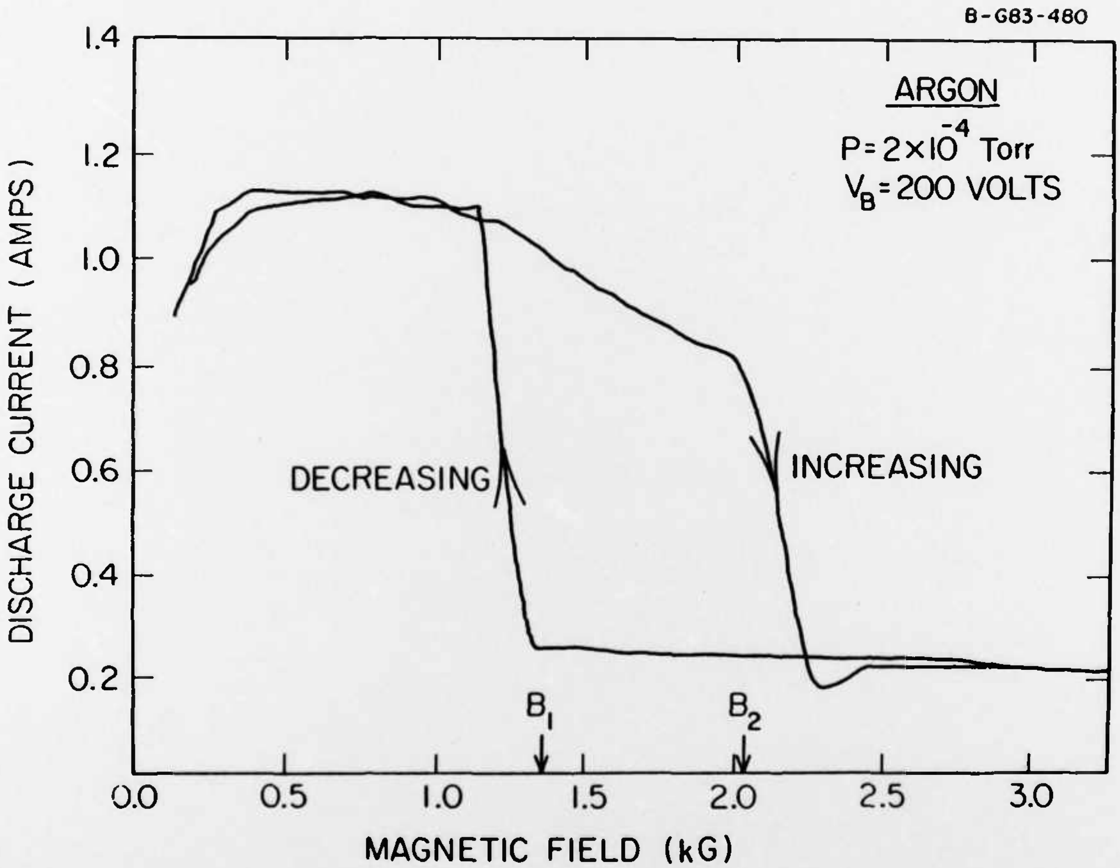

B-G83-480
ARGON
P=2×10^-4 Torr
V_B=200 VOLTS
DISCHARGE CURRENT (AMPS)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
DECREASING
INCREASING
B_1
B_2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
MAGNETIC FIELD (kG)

Fig. 5

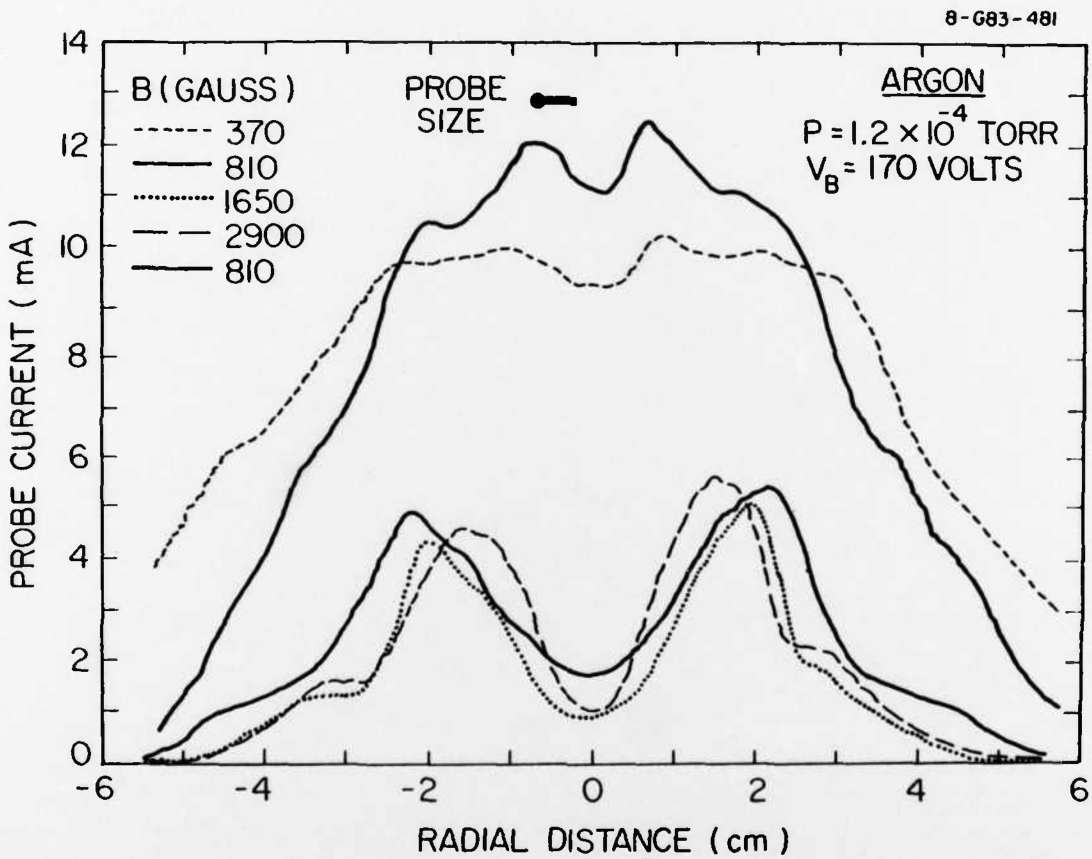
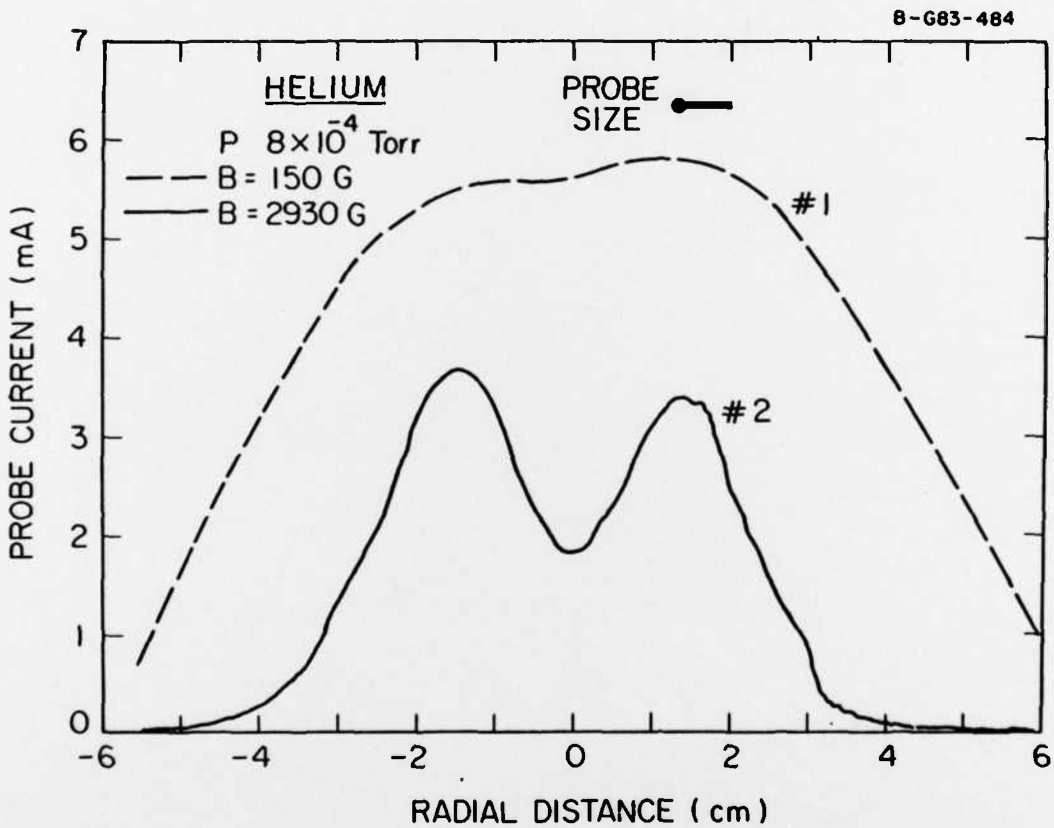
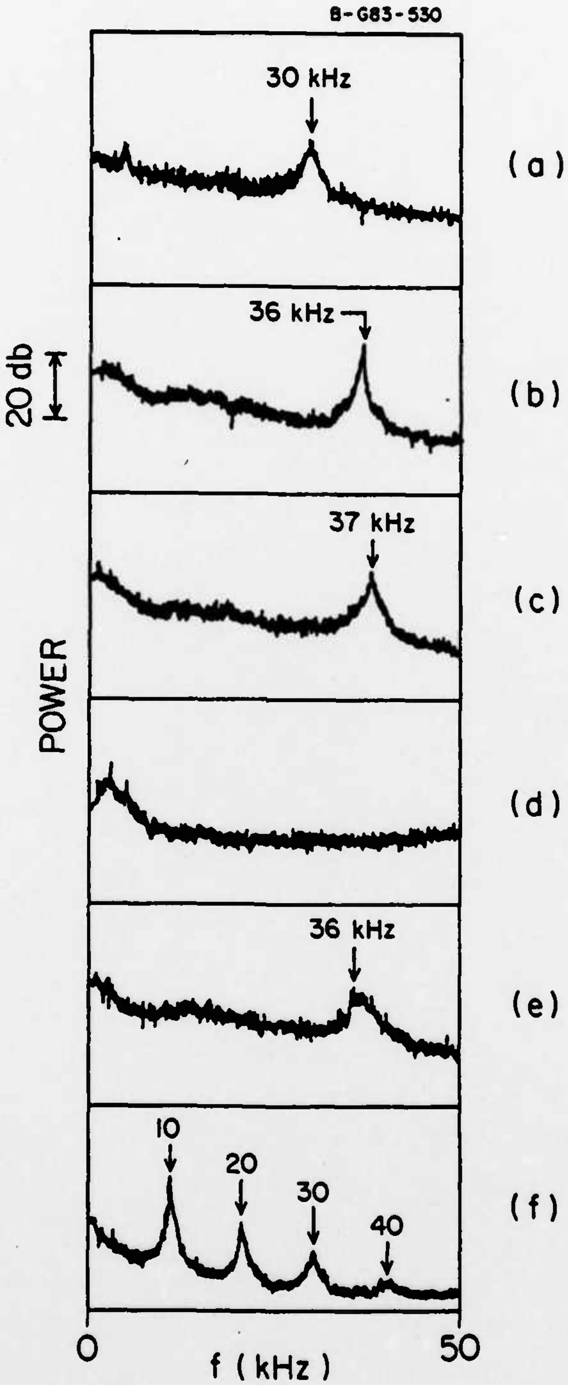

8-G83-481
B (GAUSS)
370
810
1650
2900
810
PROBE SIZE
ARGON
P = 1.2 × 10⁻⁴ TORR
V_B = 170 VOLTS
PROBE CURRENT (mA)
RADIAL DISTANCE (cm)
0
2
4
6
8
10
12
14
-6
-4
-2
0
2
4
6

Fig. 6



8-G83-484
HELIUM
P 8×10⁻⁴ Torr
B = 150 G
B = 2930 G
PROBE SIZE
#1
#2
PROBE CURRENT (mA)
RADIAL DISTANCE (cm)

Fig. 7



8-G83-530
30 kHz
(a)
36 kHz
20 db
(b)
37 kHz
(c)
POWER
(d)
36 kHz
(e)
10
20
30
40
(f)
0
50
f (kHz)

Fig. 8

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